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Marine modification of terrestrial influences on Gulf hypoxia: Part II

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Abstract

This study examines potential marine modification of two classes of terrestrial influence on Gulf hypoxia: (1) the flow of nutrient-rich water from the Mississippi/Atchafalaya River Basin and (2) the massive physical, hydrological, chemical and biological change associated with the Atchafalaya's partial capture of the Mississippi River. The latter involves repartitioning of a total flow of about 20 000 m^3 sec^{-1}, equal to that of 13 Nile Rivers, and a sediment load of 210 million metric tonnes yr^{-1},nearly 20 times that delivered by all of the rivers of the East Coast of the USA. Also involved is the loss of hundreds-to-thousands of years of stored nutrients and organic matter to the Gulf from enormous coastal wetland loss. This study found that the oceanography of the Gulf minimises the impact of both classes of terrestrial influence from the Mississippi River and its nearby estuaries on Gulf hypoxia. Oceanographic conditions give events associated with the Atchafalaya River a disproportionately large influence on Gulf hypoxia. A truly holistic environmental approach which includes the full effects of this highly dynamic coastal area is recommended to better understand and control Gulf hypoxia.

Keywords: Gulf of Mexico, hypoxia, nutrients, geology, oceanography, cabbeling, boundary current, Mississippi Trough; dissolved oxygen

Introduction

This contribution builds upon a companion study (Krug, 2007) by applying a Gulf of Mexico perspective to the hypoxic zone; in relation to how the Gulf processes inputs from the Mississippi/Atchafalaya River Basin (MARB) and coastal change, and the extent of the northern Gulf of Mexico's interaction with coastal change. In doing so, the assumptions used to define the Gulf hypoxia problem are examined further. To expand understanding of the causes and controls of Gulf hypoxia beyond MARB inputs and coastal change, an oceanographic perspective is applied to examine potential marine controls of terrestrial influences on Gulf hypoxia. The roles of oceanic, Gulf-wide and local currents, and their interactions with and within the hypoxic zone and with terrestrial inputs of water, nutrients and sediment, are examined using published literature, studies, compilations of data and satellite imagery.

Background

The National Science and Technology Council's Committee on Environment and Natural Resources (CENR) and others identify input of nutrient-rich water from the Mississippi/Atchafalaya River Basin (MARB) as the prime cause and means of control of hypoxia in the northern Gulf of Mexico (Turner and Rabalais, 1991; Rabalais *et al.*, 1999; CENR, 2000). Gulf hypoxia forms during warmer months when a warmer and less saline surface water layer develops, enabling organic matter decay to deplete dissolved oxygen (DO) in underlying water to ≤ 2 mg O_2 L^{-1}. Such hypoxic bottom water DO values have been occurring in continental shelf waters between the Mississippi River to at least the Texas border (Fig. 1). Hypoxia is lethal to many species of desirable aquatic and marine organisms (Rabalais *et al.*, 1999), although nutrient inputs can also enhance fishery production in adjacent coastal waters (Diaz and Solow, 1999).

The annual occurrence of an apparently regional seasonal hypoxia in the northern Gulf of Mexico was noticed by environmental monitoring and research programmes starting with the 1973 flood of the Mississippi and Atchafalaya rivers (Fucik, 1974; Ragan *et al.*, 1978; Bender *et al.*, 1979; Oetking *et al.*, 1979a,b; Bedinger *et al.*, 1981; Harper *et al.*, 1981; Gaston, 1985; Rossignol-Strick, 1985; Pokryfki and Randall, 1987). Since 1985, the US government has supported a Gulf hypoxia monitoring programme; its officially-reported size is that measured during the programme's mid-summer cruise. In response to the doubling of the average extent of Gulf hypoxia starting with the 1993 flood, a Watershed Nutrient Task Force was formed to solve the Gulf hypoxia problem (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 1997; 2001; Krug, 2007).

The following assumptions have been used to predict the effects of the MARB on Gulf hypoxia. Oxygen-consuming organic loading is from net algal productivity, the amount of which is dependent upon nitrogen (N) from the MARB (Turner and Rabalais, 1991; Doering *et al.*, 1999; Goolsby *et al.*, 1999; Rabalais *et al.*, 1999). Although inputs of atmospheric and oceanic N are acknowledged, the response of net primary productivity has been calculated to be directly proportional to N loading and N loading from the MARB. The N in all of the flow of the Atchafalaya River and 53 percent of the flow of the Mississippi River supports this algal growth (Turner and Rabalais, 1991; Rabalais *et al.*, 1999, p. 35). Using the assumed MARB N loading and the 290 g C m^{-2} yr^{-1} productivity figure that Sklar and Turner (1981) determined for water just offshore of the Barataria Bay estuary as the net primary productivity for 106 866 km^2 of the entire Louisiana/Texas continental shelf water west of the Mississippi, Turner and Rabalais (1991) estimated that N recycles about four times per year to support algal growth. This N recycling estimate has been retained (Rabalais *et al.*, 1999, p. 87) even though the 290 g C m^{-2} yr^{-1} estimate is no longer considered representative (Rabalais *et al.*, 1999, p. 62) — 122 g C m^{-2} yr^{-1} has come to be used for the eastern part of the hypoxic zone off the Mississippi River (Justic *et al.*, 1997; Rabalais *et al.*, 1999, pp. 81–85).

Subsequently, the Watershed Nutrient Task Force developed the *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico*. The Action Plan calls for a 30 percent reduction in MARB nitrogen (N) discharge to the Gulf to reduce the aerial extent of Gulf hypoxia from the then most recent 5-year running average of ~14 000 km^2 to a 5-year running average of less than 5000 km^2 by 2015 (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001). The Watershed Nutrient Task Force recognizes that significant uncertainties remain and there is need to reduce these to improve management options. Thus, room for improvement is planned with reassessment and the development of a new Action Plan every five years (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001); however, the deadline has since dropped back to December 2007.

Since the 2001 Action Plan there has been increased emphasis added to MARB phosphorus (P) as a nutrient of concern in controlling Gulf hypoxia (e.g. Justic *et al.*, 2003a,b, 2005; USEPA, 2004) and also a recognition that the northern Gulf of Mexico itself has become inherently more sensitive to hypoxia formation (Stow *et al.*, 2005). A history of the above institutional focus on the causes and control of Gulf hypoxia is provided by Krug (2007) who noted that during the time within which Gulf hypoxia has been observed to develop there has been essentially no overall increase in MARB inputs of water, N, and P (Turner and Rabalais, 1991; Rabalais *et al.*, 1999; Goolsby *et al.*, 1999; CENR, 2000: Kelly *et al.*, 2001; Krug, 2007). But there has been another kind of change. The Gulf environment in which Gulf hypoxia is contained is undergoing massive physical, hydrological, chemical and biological change associated with the Atchafalaya's partial capture of the Mississippi River involving a total flow of about 20 000 m^3 sec^{-1} (Goolsby *et al.*, 1999, p. 2) which is equal to that of 13 Nile Rivers (Wright and Coleman, 1973; Ludwig *et al.*, 1996) and a sediment load of 210 million metric tonnes yr^{-1}, nearly 20 times that delivered by all of the rivers of the East Coast of the USA (Curtis *et al.*, 1973). As detailed in the companion study (Krug, 2007), this type of immense river-switching, delta-building event occurs here about once a millennium. Such coastal environmental change, which includes repartitioning of MARB inputs, is capable of inducing even persistent anoxia, year-round total loss DO, and has done so prior to European settlement of the MARB. This study adopts an oceanographic perspective to examine potential marine controls of terrestrial influences on Gulf hypoxia.

Results and discussion

BOUNDARY CURRENT EFFECTS

Marine and MARB Nitrogen

The northern Gulf of Mexico has a Boundary Current flowing along its margins which strongly interacts with the hypoxic zone (Figs. 1 and 2). Such boundary currents occur along the margins of marine basins throughout the world. In the northern hemisphere the Earth's rotation deflects currents clockwise, these currents being naturally strongest in the west and weakest in the east (Greenspan, 1962;

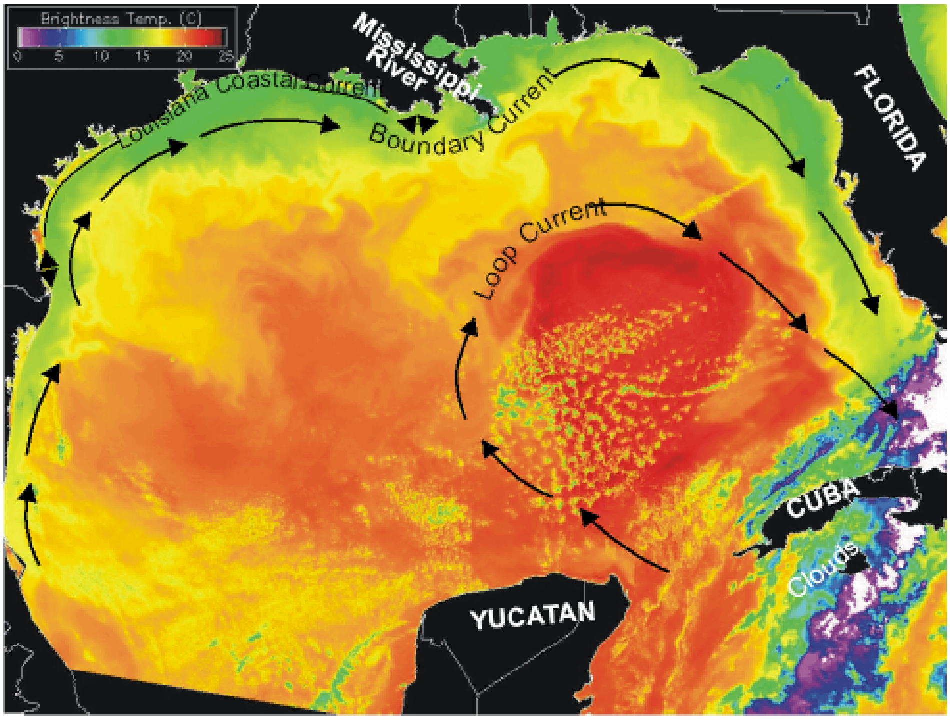

Fig. 1. *Sea surfae temperature image of the Gulf of Mexico Loop and Boundary currents. See figure description in the Appendix.*

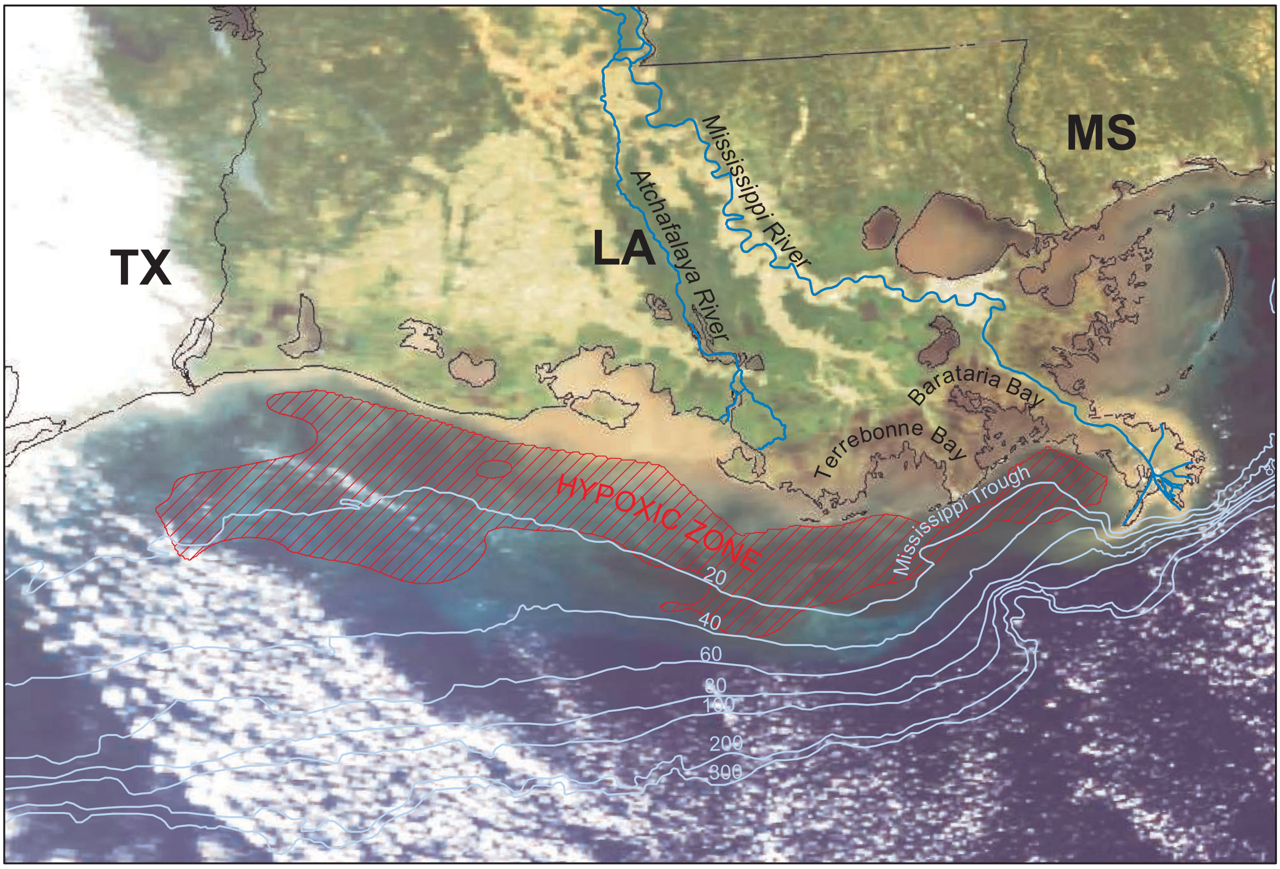

Fig.2. *The measured extent of hypoxia in 2002 (Louisia Universities Marine Consortium, 2000) in the northern Gulf of Mexico (Space Science and Engineering Center, 2002). Contour depths are in metres. See figure description in the Appendix.*

Pickard, 1979). For example, a boundary current exists in the North Atlantic Ocean and the Gulf of Mexico's Loop Current (Fig. 1) is a branch of the North Atlantic Ocean's Western Boundary Current. It enters the Gulf of Mexico by flowing north past the Yucatan, turning clockwise within the Gulf, and extends eastward through the Florida Strait between Florida and Cuba. The Loop Current reinforces the Gulf's Boundary Current (Fig. 1), annually cycling 230 million metric tons NO_3-N through the Gulf of Mexico (Blaha and Sturges, 1978). The MARB supplies an average of 1.6 million metric tons N yr^{-1} to the Gulf (CENR, 2000). Generally, this nutrient-bearing Loop Current water maintains a higher salinity, forming a vertical salinity gradient (pycnocline). The Gulf-wide pycnocline is taken to be 200 m; pycnocline depths of less than 200 m indicate net upwelling, > 200 m net downwelling. The pycnocline is 159 m for the Louisiana shelf and rises at times to above 19 m around the mouth of the Mississippi River (Blaha and Sturges, 1978). For example, Govoni and Grimes (1992) measured the upwelling of nutrient-containing high salinity water (> 36 g kg^{-1}) to less than 8 m depth just off the mouth of the Southwest Pass — the main source of Mississippi River water to the hypoxic zone.

There is an appreciable N flux through the Gulf's surface layer above the pycnocline; this flux is estimated to be about 120 million metric tons NO_3-N yr^{-1}. It is estimated that N upwelled from the deep layer below the pycnocline contributes 25 percent of biologically-utilised N in the top 10 m of the Louisiana shelf water (Walsh *et al*., 1989) and later study found that only 40 percent of N in water of the continental shelf here is from terrestrial sources of all origins (Lopez-Veneroni, 1998). Whereas MARB N is used in calculating net primary productivity and a recycling rate of N in the 106 866 km^2 of continental shelf water west of the Mississippi to the Mexican border, the presence of appreciable marine N points for the need to include marine N in calculations involving Gulf hypoxia. Indeed, the following factors indicate that the Walsh *et al.* (1989) estimate of marine N contribution is underestimated. Their upwelling estimate assumes the Loop Current is the circulation driver of the Gulf. However, the Gulf's Western Boundary Current is stronger than that induced by the Loop Current. The Gulf of Mexico has a latitudinal range large enough to set up its own Western Boundary Current (McLellan, 1965; Huang and Goodell, 1970; Sturges and Blaha, 1976; Pickard, 1979, pp. 134–158; Cho *et al.,* 1998; Wiseman and Sturges, 1998). Indeed, even estuaries the size of Chesapeake Bay are reported to have such circulation (e.g. Fischer *et al.*, 1979, p. 237). The Gulf's latitudinally-driven Western Boundary Current is strengthened by the Loop Current as well as by the prevailing winds of the Bermuda High, the latter making the Gulf's Western Boundary Current strongest in summer. It also results in the reversal of the western flow of the Louisiana Coastal Current — the thin band of coloured water inshore of the hypoxic zone in Fig. 2 and too small to be seen on the scale of the Loop and Western Boundary Currents in Fig. 1 — to the east (Kutkuhn, 1963; Blaha and Sturges, 1978; Temple and Martin, 1979; Bedinger *et al*., 1981; Crout and Hamiter, 1981; Halper *et al*., 1988; Dowgiallo, 1994; Martinez-Lopez and Pares-Sierra, 1998; Wang *et al*., 1998; Vidal *et al*., 1999; Chen *et al*., 2000; Ohlmann *et al*., 2001; Welsh and Inoue, 2002; Lee and Mellor, 2003; Zavala-Hidalgo *et al*., 2003).

This year-round Western Boundary Current induces year-round bottom Ekman upwelling that draws in nutrient-bearing water onto the Texas and Louisiana continental shelf and transports this upwelled water eastward toward the Mississippi River delta. This current also pulls in nutrient-bearing water from the cyclonic and anticyclonic deeper-water gyres off the Louisiana/Texas coast (Bogdanov, 1965; Muller-Karger *et al*., 1991; Walsh, 1991; Sahl *et al.*, 1993, 1997; Sturges, 1993; Oey, 1995; Biggs *et al*., 1996; Martinez-Lopez and Pares-Sierra, 1998; Chen *et al*., 2000; Sturges and Leben, 2000; Ohlmann *et al*., 2001; Belabbassi, 2001; Hamilton and Berger, 2002; Welsh and Inoue, 2002; Krug and Merrifield, 2006; Figs. 1 and 2).

Furthermore, as it travels north, the Western Boundary Current is pressured by and interacts with the Texas/Louisiana shoreline as its flow bends eastward, promoting much cross-shelf transfer of water off and onto the shelf where hypoxia occurs (Li *et al*., 1996; Muller-Karger, 2000; Krug and Merrifield, 2006; Figs. 1 and 2). Thus, even though Walsh *et al.* (1989) estimate appreciable non-MARB N in shelf waters, they overestimate MARB N and underestimate upwelling and upwelling's N input and enhancement of algal productivity in Louisiana shelf water.

The effect of the inflow of marine nutrients and the resulting displacement of MARB nutrients offshore need to be researched and quantified. Such water transfers affect the results that reductions in MARB N will have on Gulf hypoxia. In a review of the fate of MARB water after it reaches the Gulf, Etter *et al*. (2004) observe that there has yet to be a study designed to quantify the fate of MARB water e.g. "No detailed climatology of filing and flushing times yet exists for the Texas-Louisiana shelf, it is evident that more research is needed to characterize the fate of Mississippi River discharge in this region" (Etter *et al*., 2004, p. 18).

Interaction with Atchafalaya River Inputs

The Atchafalaya River discharges at the innermost edge at the broadest part of the continental shelf at the geographic centre of the coastline bordering the hypoxic zone (Fig. 2). Changes in the Atchafalaya River are not considered important to hypoxia formation as the amounts and proportion of MARB water and nutrients flowing down the Atchafalaya and the Mississippi have stabilised since the early 1970s (Turner and Rabalais, 1991; Rabalais et al., 1999; Goolsby *et al.*, 1999; CENR, 2000: Kelly *et al.*, 2001). However, the Atchafalaya's impact on the hypoxic zone had yet to stabilise. With the great flood of 1973, a 200 million m^3 yr^{-1} sediment load — the amount of land moved to create the Panama Canal — achieved breakthrough to the Atchafalaya Bay, with 50 percent sediment transfer efficiency to the Gulf outside the bay from where the sediment gets reworked and spread across the continental shelf (Krug, 2007). The new sediment load is so large that whereas, prior to 1973, the coastline of the western half of the hypoxic zone, Atchafalaya Bay itself and estuaries immediately to the east of the bay were losing land, after 1973 land was gained even though most mud was lost offshore and reworked in the Gulf by the erosive forces of wave, wind, current, tide and storm across the continental shelf (Wright, 1977; Roberts *et al*., 1980; Van Heerden *et al*., 1981; Wells and Kemp, 1981; Madden *et al*., 1988; Roberts, 1997). With the 1973 flood came the predicted increased efficiency of sediment transfer through the Atchafalaya and Atchafalaya Bay to the hypoxic zone (Adams and Baumann, 1980; Roberts *et al*., 1980; Donnell and Letter, 1992; Roberts, 1998; Anonymous, 1999) and the doubling of the extent of Gulf hypoxia by extension westward toward Texas and fuller coverage of the continental shelf west of the Mississippi Trough (Rabalais *et al*., 1999; CENR, 2000; Krug, 2007; Fig. 2). Gulf hypoxia formed and then expanded with the expansion of mud from the Atchafalaya River (Krug, 2007). The expanding area of fluid mud of the Atchafalaya mud stream and its loose bottom mud on the continental shelf act as fluidised reactor beds where carbon and nutrients are heavily recycled (e.g. Trefry *et al*., 1994; Aller, 1998; Abril *et al*., 1999, 2004; Rowe *et al*., 2002; Gordon and Goni, 2003; Aller *et al*., 2004; Aller and Blair, 2004; Corbett *et al*., 2004; McKee *et al*., 2004; Sutula *et al*., 2004):

"Fluid muds and mobile surface material cause the seafloor and continental boundary to act as a massive, suboxic, fluidized bed reactor... Reoxidation, repetitive redox successions, metabolite exchange, and continual mixing-in of fresh planktonic debris with refractory terrestrial components, result in an effective decomposition system largely decoupled from net accumulation" (Aller, 1998, p. 143).

Thus with the great flood of 1973, the Atchafalaya mud achieved breakthrough to the coast and permanently altered the coastal dynamics of the hypoxic zone (Roberts *et al.,* 1980; Wells 1980; Wells and Kemp, 1981; 1982; Roberts, 1998; Huh *et al.*, 2001; Draut *et al.*, 2005) creating a large and expanding area of oxygen-consuming fluidised mud reactor to deplete the oxygen from the low volumes of water inherent in these shallow water depths.

The effects of the changing Atchafalaya River, the spread of its sediment load across the dynamic, broad, reactive surface of the continental shelf on which hypoxia forms, are profound (and superimposed on the already recognized input of MARB nutrients); the influence of these sediments on Gulf hypoxia has yet to be researched and quantified.

Interaction with Mississippi River Inputs

The calculated effect of the Mississippi River discharge on Gulf hypoxia is based on idealised conditions: "Of the discharge from the Mississippi River delta, approximately 53% flows westward onto the Louisiana shelf (U.S. Army Corps of Engineers 1974, Dinnel and Wiseman 1986)" (Rabalais *et al*., 1999, p. 34).

The origin of this statement is Dinnel's 1984 M.Sc. thesis (Dinnel, 1984). U.S. Army Corps of Engineers 1974 data are the authority to determine the percentage of Mississippi River water that flows out through which outlet to the Gulf. South Pass, Southwest Pass and Grand and Tiger Passes add up to 53 percent of total flow and all of this water is assumed to flow west (Dinnel, 1984). Dinnel and Wiseman (1986) state that 53 percent of the Mississippi's discharge is assumed to move west. From this, Turner and Rabalais (1991) assumed that 53 percent of Mississippi River water supports algal production in 106 866 km^2 of USA continental shelf water west of the Mississippi (Turner and Rabalais, 1991): an assumption retained by the hypoxia assessment (Rabalais *et al.*, 1999, p. 35) upon which the Action Plan is based significantly. However, these idealised conditions are not approached in nature. There is much transfer of water on and off the continental shelf and this is especially the case with the Mississippi River. The Mississippi River discharges from the end of a land bridge which extends clear across the continental shelf. This water discharged beyond the shelf break (e.g. Ohlmann *et al*., 2001; Swarzenski, 2001; Fig. 2) often flows east and south as well as west (Lyell, 1849; Humphreys and Abbott, 1876; Woodring, 1936; Scruton, 1956; Maul, 1974; Atkinson and Wallace, 1975; Rouse and Coleman, 1976; Crout *et al*., 1984; Sturges, 1993; Dowgiallo, 1994; Li *et al*., 1997; Cho *et al*, 1998; Conkright *et al*., 1999; He and Weisberg, 2002; Welsh and Inoue, 2002; Morey *et al*., 2003a,b; Krug and Merrifield, 2006).

The eastward-flowing Boundary Current also confounds calculations based on idealised conditions because when the Mississippi River's outflow actually does flow westward it often gets blocked as it runs into this much larger eastward flow of water. As the Boundary Current approaches the far (eastern) end of the hypoxic zone, it 'hits a wall', the land bridge built by the Mississippi River:

"The large-scale geometry of the coast is not only of geomorphic interest but also of importance in determining large-scale flow patterns. The 80-km protrusion of the Mississippi delta into the Gulf of Mexico is exceeded perhaps only by Cape Cod in its ability to alter and affect the current, tidal, and wave fields operating in the local coastal waters" (Murray, 1976, p. 1).

While not perfectly contained due to the seasonal westward flow of the alongshore Louisiana Coastal Current, there is four-way convergence of surface waters over the Mississippi Trough (Fig. 2): outflows of the Atchafalaya and Mississippi Rivers, outflows of the Barataria and Terrebonne estuaries, and inflow of clear Gulf water. Convergence removes surface water by physically forcing it downward (Woodring, 1936; Ichiye, 1960; Conatser, 1971; Penland and Boyd, 1985; Levin, 1991; Hitchcock *et al.*, 1997; 2004; Krug and Merrifield, 2006). This forcing is further enhanced by the nature of the clash of river, estuary and seawaters inherent in the area around the Mississippi. The physicochemical process known as 'cabbeling' mixes masses of water of different temperatures and salinities to produce water denser than the components of its parts. Cabbeling produces vertical velocities that may be thousands of times greater than typical open water values. As distinguished by the extreme upwelling of Loop Current water around the Mississippi River Delta, seawater is advected from depth to replace seawater that mixes with freshwater (Uda, 1938; Garvine and Monk, 1974; Bowman, 1978; Bowman and Iverson, 1978; Pingree *et al.*, 1978; Govoni and Grimes, 1992; Beer, 1997; Hitchcock *et al.*, 1997; Stanton and Ostrovsky, 1998; Moum *et al.*, 2003; Nash and Moum, 2005). These conditions make the Mississippi River Delta area a locus of convergence, cabbeling and subduction of freshwater. Ichiye (1960) noted that in the area around the Mississippi River delta (27^{o}–30^{o} latitude and 87^{o}–92^{o} longitude) "the salinity in the upper layers is so variable that the average picture obtained by simply putting together all data available seems to be meaningless" (p. 71).

"At the continental slope near the mouth of the Mississippi...the temperature at a depth of 100 m changed by 2^{o}–3^{o} within a few hours...obviously a result of internal waves associated with the tides. It is clear that this region is very dynamic. In the open sea the temperature fluctuations within the same period were within the range of 1^{o}" (Bogdanov, 1965, p. 19).

Analysis of 1471 Gulf water profiles down to 1000 m depth from April 1998 to December 2002 (Weatherly *et al.*, 2003) show that freshwater from the Mississippi River is subducted into the depths (1000 m or more) of the Gulf — 867 inversions were found in the 1471 profiles. Of these inversions, 96 percent were seen above 160 m depth. Average depth was 32 m. Inversions clustered within 400 km of the Mississippi River and inversions persisted over time and space, indicating large volumes of water. The floats used to measure inversions typically drifted several 10s of km a day in their 7-day cycles and inversions commonly persisted through the 7 days (Weatherly *et al.*, 2003). Temperature and/or salinity inversions also were seen by others (e.g. Dodge and Lang, 1983; Brooks and Legeckis, 1982; Lugo-Fernandez, 1998; Conkright *et al.*, 1999; Wawrik and Paul, 2004). Clearly nutrients in such subducted Mississippi River water are not available to support algal growth at the surface of the hypoxic zone.

Overall, currents of the continental shelf induce manifolds through which off-shelf water is advected onto the shelf and shallow shelf waters are advected offshore and down into waters up to 2000 m deep (Hunter, 2001). Coastal freshwater outbreaks in the north-west Gulf of Mexico can be of the order of the entire current flow through the Gulf of Mexico, over 30×10^6 m^3 sec^{-1}, which is more than 600 times the instantaneous flow of the MARB to the Gulf of Mexico (Brooks and Legeckis, 1982). The area around the Mississippi River Delta is a locus of onshore/offshore transfer of water (Ohlmann *et al.*, 2001) where marine nutrients become available to support algal growth and where river water is no longer available to support algal growth.

For the Boundary Current there is such a manifold favouring offshore and onshore flow of water in front of and parallel to the land bridge built by the Mississippi. The two most prominent physiographic features of the region, the Mississippi River Delta and the Mississippi Canyon/Trough (e.g. Coleman *et al.*, 1982, p. 519), are in close proximity and parallel each other. The Canyon has extended itself inland as a trough almost to the shoreline of the Timbalier and Barataria estuaries just west of the Mississippi River delta and it has extended itself offshore as the major sediment fan of the Gulf of Mexico. The Mississippi Trough and Mississippi Canyon are a by-pass system that feeds the mud-rich Mississippi Fan which lies at the bed of the Gulf of Mexico (e.g. Stuart and Caughey, 1976; La Blanc and Steffens, 1986; Burden, 1999; Nelson 2002; Nelson *et al.*, 2002). Bathymetry dating back to the 1700s (United States Coast Survey, 1861, 1863; Fig. 1) and modern sediment sampling (Corbett *et al.*, 2004; McKee *et al.*, 2004) indicate that these dynamic currents have maintained the Mississippi Trough essentially as is. It has been maintaining its features while accumulating just enough sediment to compensate for land subsidence in the face of a river system that delivers nearly 20 times the sediment load of all of the rivers on the entire East Coast of the United States, 70–75 percent of which is directed to the west toward the direction of the trough (Scruton, 1956; Curtis *et al*., 1973). Radioisotope studies show that this sediment is being deposited within 30 km of the Mississippi River Delta (Corbett *et al*., 2004; McKee *et al.*, 2004). Similarly, there is a sharp decline in both algal productivity and dissolved nutrient content of Mississippi River water; as with the river's sediment, the bulk of the algae produced by Mississippi River water settle here (Riley, 1937; Thomas and Simmons, 1960; Lohrenz *et al.*, 1990, 1997, 1999; Lopez-Veneroni and Cifuentes, 1994; Smith and Hitchcock, 1994; Rabalais *et al*., 1996, 1999; Scavia *et al.*, 2003) to be, like the bulk of the terrestrial sediment deposited here, transported offshore and downslope into the deeps of the Gulf of Mexico.

As noted by Goodbred and Kuehl (1999), troughs and canyons persist near the mouths of rivers delivering great loads of sediment by actively depositing sediment offshore. The conclusion derived from the existence of the canyon in an otherwise extremely flat continental shelf (e.g. Scruton, 1956; Stuart and Caughey, 1976; Darnell *et al*., 1983; National Ocean Service, 1985) in the high sediment deposition area immediately to the west of the Mississippi River is that this is a preferential area of offshore movement of sediment as well as water.

The effect of the Boundary Current/Mississippi Delta/ Mississippi Canyon system's transport of water, dissolved nutrients, sediment and organic matter away from the hypoxic zone has yet to be researched and quantified.

Spring/Summer Although eastward movement of discharged Mississippi River water away from the hypoxic zone can occur at all times of the year, the warm months are a special case where eastward movement is common and can predominate. For six months of the spring and summer the prevailing winds of the Bermuda High strengthen the eastward flow of the Boundary Current and act to drive nearshore waters, the Louisiana Coastal Current, eastward and away from the Mississippi Trough (Scruton, 1956; Linton, 1968; Murray, 1976; Blaha and Sturges, 1978; Oetking *et al.*, 1979a; Bedinger *et al*., 1981; Sklar and Turner, 1981; Crout and Hamiter, 1981; Halper *et al*., 1988, Martinez-Lopez and Pares-Sierra, 1998; Wang *et al*., 1998; Chen *et al.*, 2000; Lugo-Fernandez *et al*., 2001; Welsh and Inoue, 2002). Its prevalent summertime eastward movement along the Louisiana shelf can be viewed on the hundreds of satellite images displayed by Krug and Merrifield (2006).

This shift to easterly flows has long been recognized as being biologically significant. For example, as part of an expanded NOAA research effort into the Gulf shrimp fishery (Kutkuhn, 1963), extensive research was conducted on currents along the USA Gulf coast (Temple and Martin, 1979). This NOAA research found there was a seasonal pattern in currents induced by seasonal changes in prevailing winds, citing 11 previous studies in support of this observation of seasonal eastward flow (Temple and Martin, 1979). Furthermore: "Physical oceanographers have suspected the Mississippi River (MR) as a source of low-salinity water in the Gulf Stream and Florida Straits (Wennekens, 1959; Atkinson and Wallace, 1975; Maul, 1974)..." (Ortner *et al*., 1995). This 'Green River' of chlorophyll-enriched, freshened water was observed at least as early as 1962 (Khromov, 1965, p. 39). Since the 1970s, satellite observations have come to supplement traditional observations of the Green River, the movement of Mississippi River water east from its outlet and as far down as into and through the Florida Straits (Maul, 1977; Ortner *et al*., 1984; Muller-Karger *et al*., 1991; Gilbes *et al*., 1996; Wang *et al*., 1998; Chen *et al.*, 2000; Paul *et al.*, 2000a,b; Muller-Karger, 2000; Del Castillo *et al.*, 2001; He and Weisberg, 2002; Hu *et al*., 2003; Morey *et al*., 2003a,b; Toner *et al*., 2003; Wawrik *et al*., 2003; 2004; Wawrik and Paul, 2004; Krug and Merrifield, 2006). During the warm season, Mississippi River water does not typically attach itself to the coast west of the Mississippi River delta to move west in the Louisiana Coastal Current (Rabalais *et al.*, 1999, p. 33). Indeed, the prevalent seasonal movement of the Louisiana Coastal Current is east toward the Mississippi River.

These findings show that the previously held view overemphasised the effect of the Mississippi River in creating and sustaining a warm season cap of water under which hypoxia forms. They also show that there is less Mississippi River N and other nutrients than is calculated to support algal production in the hypoxic zone in the warm season. These findings need to be further developed and integrated into calculations of the effects of MARB N, nutrients and water on Gulf hypoxia.

Interaction with Barataria and Terrebonne estuarine inputs
The basins containing the Barataria and Terrebonne estuaries are exemplars of nutrients and organic matter stored over thousands of years that are bleeding into the hypoxic zone from massive wetland loss: 80 percent of tidal wetland loss for the entire continental USA occurs in the Mississippi River Delta (Roberts, 1994). Barataria Bay occupies about 10 percent of the coastline of the hypoxic zone. By the early 1970s, Barataria Bay was estimated to be imposing an oxygen demand on coastal waters equal to that of total net primary productivity of the hypoxic zone itself through a

net daily flushing of 230 million m^3 day^{-1} (Happ *et al*., 1977; Krug, 2007). Since then, Barataria Bay has almost doubled in size and is still growing. Barataria and Terrebonne Bays occupy about 30 percent of the shoreline of the hypoxic zone and their combined daily outflow to the Gulf was estimated to be about three times that of the Barataria alone (Swenson and Swarzenski, 1995). Both basins continue to lose land and their bays continue to grow (Martin *et al*., 2000; USGS, 2003): "The escalating volume of freshened and warmed estuarine water being flushed daily into the hypoxic zone changes coastal hydrology to increasingly favor the development of hypoxia. This increasingly-favorable hydrology combined with the outflow of hundreds-to-thousands of years of accumulated oxygen-consuming nutrients and organic matter, and highly productive estuarine water, all act in concert to increasingly promote hypoxia as marine transgression progresses along the disintegrating coastal lands of the eastern half of the hypoxic zone" (Krug, 2007).

Unlike the Mississippi River, whose outlets discharge beyond the shelf break and into the face of the Boundary Current, the outlets of Barataria and Terrebonne Bays discharge on the innermost side of the continental shelf and, therefore, should be more effective in promoting hypoxia than Mississippi River water by movement east and west in the Louisiana Coastal Current. On the other hand, since the Mississippi Trough approaches the outlets of both estuaries, there will also be interaction between the trough and estuarine outflows. Thus, it is expected that water, nutrients and sediments discharged from these basins will be less effective in promoting hypoxia west of the Mississippi Trough than that discharged by the Atchafalaya River as these estuaries are located immediately in front of an oceanographic manifold favouring offshore/onshore flow: "Brackish water plumes in shelf water and their mass continuity counterpart, landward flowing shelf bottom water, are both powerful components of the more general coupled circulation between estuaries and the continental shelf. Because of the very low frequencies at which they operate, including the climatological mean state, they contribute greatly to net displacement of water and thus are both certain to exert critical impacts on both estuarine and shelf ecology" (Garvine, 1986, p. 64).

The effect of the changing hydrology, nutrient and material from wetland loss on Gulf hypoxia has yet to be adequately researched and quantified.

Conclusions

This study builds upon a companion study (Krug, 2007) by applying a Gulf of Mexico perspective to the hypoxic zone; how the Gulf processes inputs from the MARB and coastal change, and how the Gulf interacts with coastal change. In doing so, assumptions used to define the Gulf hypoxia problem were further examined. The MARB supplies 1.6 million metric tons N yr^{-1} to the 230 million metric tons NO_3-N which flows through the Gulf every year, of which 120 million metric tons NO_3-N is upwelled. Whereas calculations of the MARB's effect on Gulf hypoxia assume that MARB N is the only source of N for the 106 866 km^2 of the continental shelf water between the Mississippi and the Mexican border, this was found not to be the case. The Western Boundary Current, Loop Current and wind-derived currents favour upwelling onto the Texas and Louisiana continental shelf and/or downwelling and offshore transport of shelf water. Upwelling and offshelf/onshelf water transfers are most favoured along the Louisiana coast and it is here that marine nutrient inputs are favoured to support algal production and where loss of MARB nutrients offshore is also favoured.

The Gulf of Mexico's oceanography minimises the relative effectiveness of the Mississippi River inputs on Gulf hypoxia. The above-calculated effect of Mississippi River discharge on Gulf hypoxia is based on the idealised assumption that all water discharged from the Atchafalaya and from the Mississippi's South Pass, Southwest Pass, and Grand and Tiger Passes, 53 percent of the Mississippi's total flow, flows west to support algal production in the 106 866 km^2 of USA continental shelf water west of the Mississippi. Nevertheless, the Mississippi River discharges from the end of a land bridge which extends clear across the continental shelf to discharge much of its waters beyond the shelf break. Out here, discharged waters flow east and south as well as west. During the summertime when hypoxia occurs, predominant flow is east, away from the hypoxic zone. Water that does move west runs into the Gulf's Boundary Current. The convergence of Gulf and river waters has maintained the Mississippi Trough through the forcing of water, sediment and decaying algae downtrough and offshelf. Such water, nutrients and organic matter are unavailable to support hypoxia.

Oceanographic factors enhance the Atchafalaya's influence on Gulf hypoxia. Most hypoxia occurs on the broad, flat, shallow continental shelf west of the Mississippi Trough and it is here that the extent of hypoxia has expanded. Atchafalaya River water, nutrients and sediments discharge into the innermost edge of the broadest part of the continental shelf at the hypoxic zone's geographic centre. Water, nutrients and sediment are spread east, west and south throughout the hypoxic zone. Starting with its sediment load breakthrough during the 1973 flood, and its enhancement with the 1993 flood, Atchafalaya River mud has been expanding along the coast and along the bottom of the hypoxic zone. The expanding area of fluid mud is acting as an expanding fluidised reactor bed where carbon and nutrients are heavily recycled, depleting DO from the relatively small volumes of overlying shallow water. And with this expansion of reactive fluidised mud, Gulf hypoxia has also been expanding, superimposing its effects upon the MARB influences already recognised.

The oceanographic controls on water, nutrient and sediment output from the Barataria and Terrebonne estuaries appear to be intermediate between that of the Mississippi and Atchafalaya Rivers. Whereas these estuaries discharge at the innermost part of the continental shelf, they do so at the eastern edge of where hypoxia forms and into the mouth of the Mississippi Trough which lies just offshore of their outlets.

It is recommended that a broadened approach for better understanding the causes and controls of Gulf hypoxia be adopted including, but not limited to, MARB inputs and coastal change and marine processing of terrestrial and Gulf influences.

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Appendix

Figure 1 The spectrum of sea surface temperatures ranging from red through green illustrates the flow of the Gulf of Mexico's Boundary Current and its Loop Current on 23 February 2003. Fluid lines defining coloured areas depict regimes of sea surface temperatures of the Gulf of Mexico. Sharp, speckled and streaked coloured (temperature) features and areas of white are clouds. The area of deepest red represents warm Caribbean seawater passing into and through the Gulf with the Loop Current. The Boundary Current along the margins of the Gulf is highlighted by cold upwelled water flanked inshore and offshore by warmer waters. The westward flow of Mississippi River water stops and then falls back on itself much as a fountain does in trying to overcome the downward pull of gravity. In this case, the force operating against the Mississippi's westward outflow is the eastward motion of the Gulf's Boundary Current. The eastward flow of cold water out of the third bay to the west of the Mississippi is the outflow from the Atchafalaya River (see Fig. 2 for greater detail). The Louisiana Coastal Current is a nearshore current too small to generate features comprehensively discernable at the scale of this figure. The Coastal Current's direction of flow is reversible and sensitive to prevailing wind direction.

Additional supporting satellite imagery for this day can be accessed through the Space Science and Engineering Center website: http://eosdb.ssec.wisc.edu/modisdirect/historical/. Higher resolution sea surface temperature and turbidity satellite images of the Mississippi River Delta and the area of the Atchafalaya River for this day can be accessed on the Louisiana State University's Earth Scan Laboratory website: http://www.esl.lsu.edu/research/NOAA_AVHRR/archive_baywatch.php?day

Chlorophyll images for this day are available from the NASA website: http://oceancolor.gsfc.nasa.gov/cgi/level3.pl

A complilation of related images is posted by the Illinois State Water Survey (Krug and Merrifield, 2007).

Figure 2 The distribution of green, yellow, brown and blue colours is informative of what is happening in this 22 May 2002 view of the northern Gulf of Mexico. White is cloud. Deep blue is indicative of clear Gulf water; blues with milky casts are consistent with the presence of coccolith algae (whose carbonate shells make chalk). The strong eastward movement of the Gulf's Boundary Current across the bottom of this picture is better viewed during the cool months (e.g. Krug, 2007; Krug and Merrifield, 2006). The Boundary Current interacts dynamically with shelf water, Atchafalaya River water and Mississippi River water, and the waters of various estuaries — as indicated by the distribution of yellow and brown sediment-laden water and green algae water. Much water from the Atchafalaya River and its nearby shelf area is moved offshore and east to over the Mississippi Trough where it is blocked from further eastward movement by the inflow of Gulf water. The same happens to water issuing from the Mississippi River's southwest outlet and the offshore outflows of the organic-rich brown waters of the Terrebonne and Barataria estuaries at the head of the Mississippi Trough. The Atchafalaya empties into a bay from whose westernmost part the yellowish muddy Louisiana Coastal Current flows westward toward Texas. Water offshore of this coastal current is generally moving eastward in concert with the Boundary Current.

Additional supporting satellite imagery is available as documented for Fig. 1.

Kathy Brown is thanked for making both images.